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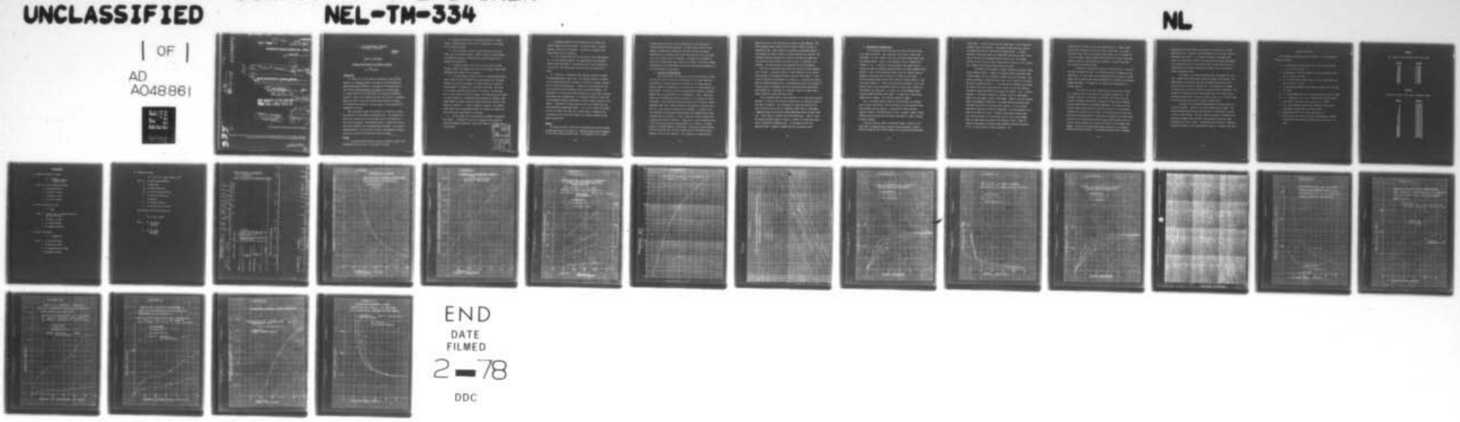

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10 Paul O. Laitinen

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*U. S. Navy Electronics Laboratory, San Diego 52, California*

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U. S. NAVY ELECTRONICS LABORATORY
SAN DIEGO 52, CALIFORNIA

NE051600
(L2-4)

TECHNICAL MEMORANDUM

# DESIGN CHARACTERISTICS OF PROPOSED SONODIVER

By
Paul O. Laitinen

## INTRODUCTION

Mr. Gordon Wenz of Code 2322 has expressed a desire for the design of an underwater device to measure sea noise to depths of about 12,000 feet. is required. He called a conference on 17 February 1959 in Bldg. 106 to discuss technical requirements and specifications. It is desired that the Mr. Wenz pointed out the desirability of recording equipment be contained in a body to be launched from ships that sink to a prescribed depth, stay there during the recording time interval and rise to the surface after recording. The body sends a homing signal and is recovered by the ship.

This memorandum presents the results of an analysis of design requirements for the proposed hydrodynamic body. The analysis indicates that a simple and relatively light body can be designed to meet the requirements. The proposed body has a double hull with the inner hull containing the instruments being resistant to the hydrostatic pressures. The outer hull is used for hydrodynamic considerations and to provide the driving and release weights.

## SUMMARY

1. Structural considerations of elastic stability, stress, and deformation favor the use of a spherical inner hull.

2. Stress and deflection characteristics indicate a shell radius - thickness ratio of 40 or less is desirable. (.15 inches for a 12 inch diameter).

3. The requirement of small transit times down and up and large load favor thinner shells. Figure 14 shows the load capacity for spheres and Figure 15 indicates the required return time of spheres from 12,000 feet.

4. A half-hour return time requires 1.1, 1.3, and 1.7 foot diameter spheres for payloads of 10, 20, and 50 pounds, respectively. Accessories are included in the payload.

5. A 1.5 foot sphere of R/t of 40 and a 20 pound payload would have a total trip time to 12,000 feet of 68 minutes for a 15 minute descent and 30 minute recording. It would require 62.8 pounds of driving weight for descent for a spherical outer hull. The weight at the surface would be 77.82 pounds on retrieval. It would jump about 2 feet above the surface on ascent. The shell unit stress would be about 104,000 psi. Compression would decrease the buoyancy .9153 pounds while the density variation would increase the buoyancy 2.240 pounds at 12,000 feet. Careful weighing is required. The buoyancy would differ about 1.325 pounds between the surface and 12,000 feet. This differs with geographical sea location.

6. A final design will be determined by equipment requirements and tactics. A practical design for a reasonable total weight of about 100 pounds and retrieved weight of 75 pounds is feasible for a 20 pound load.

7. Practical weight release mechanisms can be designed for bodies designed for various depths. To stop the body, a pressure sensitive release can be designed. To surface, a corrosion type weight release may be preferred.

8. The estimated shop time to make forms is about 300 manhours for a 1.5 foot diameter sphere. The sphere would be manufactured outside of the Laboratory. The estimated cost of metal spinning is about $20.00. The sheet steel should cost much less than $2.00 a pound.

9. Steels can be obtained having ultimate strengths in excess of 250,000 pounds per square inch. The ultimate strength is defined as the highest unit stress a material can sustain in tension, compression, or shear before rupturing. Varying the carbon content and the heat treatment is used to produce steels of various strengths. The introduction of various other alloys controls the grain size, structure, and produces some strengthening. The American Institute of Steel and Iron classifies steels as conforming to certain chemical limits by AISI numbers. Commercial "H" steels conform to the AISI numbers and also have controlled hardenability limits. One of these steels can be used to make the shells that will have a safety factor in excess of 2.5. The safety factor is the ratio between the ultimate strength and the design stress value.

## RESULTS

The shell structure containing the instruments must provide proper hydrodynamic behavior in addition to withstanding hydrostatic pressures of about 5400 pounds per square inch. It is desirable to have small

transit times from and to the recording depth and the body must be nearly stationary during recording. The body design requires a high degree of hydrodynamic stability so the body will move vertically. Neglecting ocean currents, such a body would reappear at the same position at the surface as it was released. The body can be designed to move fast at depths where ocean currents are likely. The various design considerations are listed below along with an accompanying discussion of the calculations that were made.

1. Structural considerations

The pressure hull in addition to be able to withstand the external pressure must be light for a large payload. The light structures may fail due to elastic stability in addition to too large stresses. Elastic stability is determined by the stiffness of the structure not by its strength. The loads in thin structures produce bending or twisting moments that are proportional to the deflections. Axially symmetrical bodies can withstand large external pressures and not buckle to elastic instability. The sphere has the most stability with the eggs or prolate spheroids being next. Elastic stability is evaluated by critical loads. This is an upper limit for failure due to buckling. In shells due to the likelihood of geometrical irregularities, the loading should be considerably less than critical. Figure 1 shows the critical pressure for a sphere under external pressure. A sphere with a radius thickness ratio of 50 (.12 inches thick for a foot diameter) can withstand a critical pressure of 13,700 pounds per square inch. For spheres of R/t less than about 70 under 5400 psi, the wall thickness will be determined by its stresses and not by its stability. For a cylinder of length diameter

ratio of one (R/t = 40), the critical pressure is only 1230 psi. Support stiffness must be used to obtain a higher critical pressure as normally is done. When a sphere is stretched or compressed along an axis through its center, prolate or oblate spheroids are obtained. The buckling resistance depends on the ratio of the major and minor axes. The larger the ratio becomes the weaker the body of revolution is to buckling. Any body shape can be strengthened by using stiffeners.

For use at great depths with small body weights, the unit stresses will be large. A spherical shell of a given thickness has the smaller unit stresses for an external pressure load than other shapes. A unit stress of 130,000 psi compression is produced in a spherical shell under 5200 psi external pressure with a radius-thickness ratio of 50 (Figure 2). Various steels are available that allow working stresses considerably over 100,000 psi. Generally on an allowable stress per pounds weight basis, steels are better than most metals.

A very important factor is the deformation of the body under external pressure. The size of the shell is decreased and the displaced weight of the body is decreased. It is desirable for depth discrimination and small hovering rates to have the displaced weight increase with depth. A spherical shell has the least volume displacement under external pressure. Thick walls are required for small deformations. Figure 3 shows the buoyancy weight change of a sphere at 12,000 feet depth with variation of radius-wall thickness ratio. A foot sphere of R/t of 50 decreases about .3 pounds at 12,000 feet from its surface value.

2. Hydrodynamic Considerations

It is desirable that the descent and ascent times of the body be as short as possible. The relocation of the body is easier with less drift. For fast falling rates, the body must be much heavier than its buoyancy weight. Figure 4 shows buoyance weight of spheres for a density of 1.04. A sphere one foot in diameter must weigh about 45 pounds more than its buoyancy weight to attain a 10 knots (16.8894 ft/sec) velocity. With a good streamlined shape of the same diameter about 10 pounds over buoyance would be required to attain the same speed. A two foot diameter sphere requires four times the driving weight of a one foot sphere (Figure 5). Outer hull construction furnishes a way to add driving weight in any streamlined fashion and still have a strong pressure chamber for instruments. In ascent, the driving weight equals buoyancy weight less total body weight. To ascend fast, considerable weight must be dropped. This cuts the available payload.

For a ten minute ascent or descent of 12,000 feet, the velocity must be equal to 20 ft/sec. The time required to attain terminal velocity is small even for spheres. A foot diameter sphere attains a terminal velocity of 16.8894 ft/sec in about 3 seconds. Figure 6 shows velocity plotted against time for spheres designed to attain a 10 knot terminal velocity.

After the body has reached a prescribed depth, a portion of the outer shell is dropped using a pressure release mechanism. Figure 7 shows the velocity after weight release for an assumed initial velocity

of 10 knots. A one foot diameter sphere slows down to .086 ft/sec from 16.8894 ft/sec in 100 seconds. The smaller spheres slow down quicker. Increasing the drag will slow down the bodies quicker. An oblate spheroid of the same diameter and weight will slow down in about 75 percent of the time for an length/diameter ratio of 3/4. The fastest braking action is that of a disk, being about 41 percent of time required for a sphere of same cross sectional area and weight.

The body must be designed to remain relatively stationary during sound recording period. A smooth foot diameter sphere could move about 2 ft/sec (Figure 8) and not probably produce recordable flow noise. For usable recordings, the body should not move too far during the estimated 30 minute recording interval. A .10 ft/sec average velocity would change the location 180 feet in one half-hour. Figure 9 shows the velocities produced by weight difference from buoyancy for spheres. For a .10 ft/sec velocity, a foot sphere requires an unbalance weight of .0036 pounds while a two foot sphere requires .0144 pounds. Based on the same Reynolds Number or turbulence ratings; the same weight unbalance produces equal flow noise values for all diameters with spheres. The use of oblate spheroids or disks will reduce the velocities. The best reduction is to about 64 percent with a disk. Although a small sphere tolerates the same weight unbalance as a large sphere for the same Reynolds Number, this is a much larger percentage of the buoyance weight. Figure 10 shows the percentage of buoyancy weight unbalance producing velocities of .1, .5, and 1 ft/sec for sphere diameters. The

design buoyancy weight of a one foot spherical body of infinite stiffness differs .64 pounds from the surface to 12,000 feet. The design buoyancy weights differ 5.31 pounds between depths from 0 to 12,000 for a two foot sphere. Bigger bodies allow larger actual weight variations. Figure 11 shows the drift velocities produced by being 100 feet from the position of neutral buoyancy.

In order to insure depth sensing, the body must have a restraining force dependent on depth. The restraining force of damping does not insure this. The body during the hovering period is the mass in a spring system with the spring force being furnished by the difference of buoyance weight with depth. The damping is not linear being proportional to velocity squared.

The density of the ocean always increases with depth although not a constant rate due to salinity, variations, currents, etc. The Carnegie Institution of Washington Publication 545 "Observations and Results in Physical Oceanography" tabulates the recordings of physical characteristics during the 1928-1929 Expedition. The density near the surface varies considerably from location to location but is much more constant with location at great depth. The density variations are tabulated for Station 132 (Table II) used in this analysis under Computations. The increase in density increases the buoyancy force (Figures 12 and 13 show the weight increase due to density variation and compression with depth). In general for elastically stable spheres, the net buoyancy weight increases with depth. A foot sphere increases about .64 pounds

from surface to 12,000 feet due to density variations while a 2 foot sphere increases 5.3 pounds. Body compression has the reverse effect of decreasing body weight. A foot sphere of R/t of 50 decreases .229 pounds due to compression while a two foot sphere decreases 2.82 pounds. It is desirable to have the body stiff enough so that there can be no regions where the buoyancy decreases with depth due to a slow rate of density change with depth.

The effect of increasing buoyancy weight with depth is to produce a stable oscillating spring system with unlinear $C\dot{X}^2$ damping. For rigid spheres, the period of the system is 1060 seconds based on the average density variation at station 132. It corresponds to a damped non linear system with the solution depending on initial conditions. The system being highly damped for spheres insures the body positioning at the local buoyancy point relatively rapidly for the case of not too large an initial displacement from the neutral buoyancy point.

The motion of the bodies during descent and ascent should be as vertical as motion. Spheres do not tend to pitch when in motion. All long streamlined shapes tend to nose and must be stabilized by the use of fins or other devices. The same terminal velocity is obtained by one fourth the driving weight for equal cross sectional areas by a well-streamlined body over a sphere. Streamlining and stability in pitch are obtainable together if the streamlining is done by a weighted outer hull.

## REFERENCES

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2. S. Timoshenko, Theory of Elastic Stability, McGraw-Hill Book Co., New York, N.Y. 1936.
3. R. J. Roark, Formulas for Stress and Strain, McGraw-Hill Book Co., New York, N.Y. 1954.
4. H. Schlichting, Boundary Layer Theory Pergamon Press, New York, N.Y. 1955.
5. H. Lamb, Hydrodynamics, Dover Publications, New York, N.Y. 1945.
6. C. D. Perkins and R. E. Hage, Airplane Performance Stability and Control, John Wiley & Sons, New York, N.Y. 1949.
7. G. M. Wenz, Sonodiver-Preliminary Technical Requirements, Memorandum from Code 2322, 11 February 1959.
8. Hydrographic Office, H.O. 614, Washington, D.C.
9. Observations and Results in Physical Oceanography, Carnegie Institution of Washington Publication 545, Washington, D.C. 1945.

## TABLE I

MEAN DENSITY ABOVE INDICATED DEPTH FROM HO 614

| Meters | Density |
|---|---|
| 200 | 1.0255 |
| 400 | 1.0267 |
| 600 | 1.0276 |
| 800 | 1.0283 |
| 1000 | 1.0289 |
| 1500 | 1.0304 |
| 2000 | 1.0318 |
| 2500 | 1.0331 |
| 3000 | 1.0356 |
| 4000 | 1.0369 |

## TABLE II

DENSITY IN PACIFIC STATION 132, SEPTEMBER 8, 1929

| Meters | Density |
|---|---|
| 0 | 1.023.66 |
| 5 | 1.023.69 |
| 23 | 1.023.77 |
| 47 | 1.024.78 |
| 70 | 1.025.15 |
| 93 | 1.025.39 |
| 185 | 1.026.25 |
| 279 | 1.026.90 |
| 374 | 1.027.52 |
| 471 | 1.027.92 |
| 673 | 1.028.62 |
| 711 | 1.029.27 |
| 1015 | 1.030.47 |
| 1513 | 1.032.14 |
| 1997 | 1.034.70 |
| 2440 | 1.037.21 |
| 2891 | 1.039.60 |
| 3304 | 1.041.95 |
| 3715 | 1.044.26 |

## COMPUTATIONS

1. Elastic Stability of Sphere

$$P^1 = \frac{2E\,t^2}{R^2\sqrt{3\,(1-\gamma^2)}}$$

where $P^1$ is the critical pressure

$E$ is Young's modulus

$\gamma$ is Poisson's Ratio

$R$ is radius of shell

$t$ is shell thickness

2. Stress in Spherical Shell

$$S = \frac{P\,R}{2\,t}$$

where $S$ is unit hoop or meridinal stress in pounds square inch

$R$ is radius of shell

$t$ is shell thickness

$P$ is external pressure

3. Radial Deformation

$$\Delta R = \frac{R\,S\,(1-\gamma)}{E}$$

where $R$ is the shell radius

$S$ is unit hoop stress

$E$ is Young's elastic modulus

$\gamma$ is Poisson's ratio

4. Equation of motion

$$(M + M_v)\ddot{X} = (M - M_B)g - 1/2\, C_D\, \rho\, S\dot{X}^2$$

where $C_D$ is body drag coefficient

$M$ is body mass

$M_v$ is body virtual mass

$M_B$ is mass of displaced water

$S$ is cross sectional area

$X$ is distance

$\rho$ is the water density

$g$ is acceleration of gravity

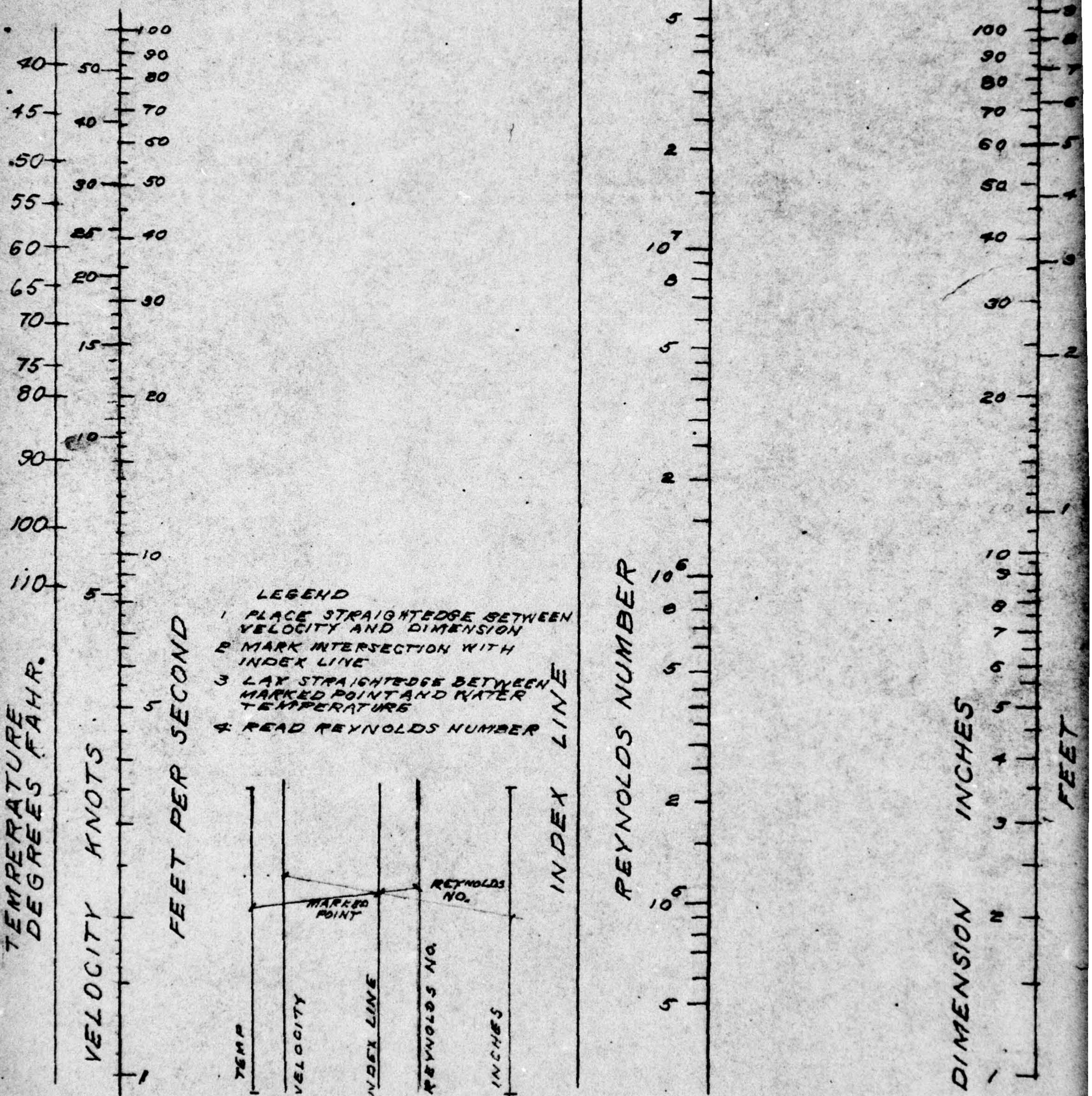
The solution of the above equation is

$$\dot{X} = a \sin h\ g^1/a^t$$

where $a$ is $\dfrac{(M - M_B)g}{1/2\, C_D\, S}$

$g^1$ is $\dfrac{(M - M_B)g}{(M + M_v)}$

# REYNOLDS NUMBER IN WATER AT NORMAL TEMPERATURES

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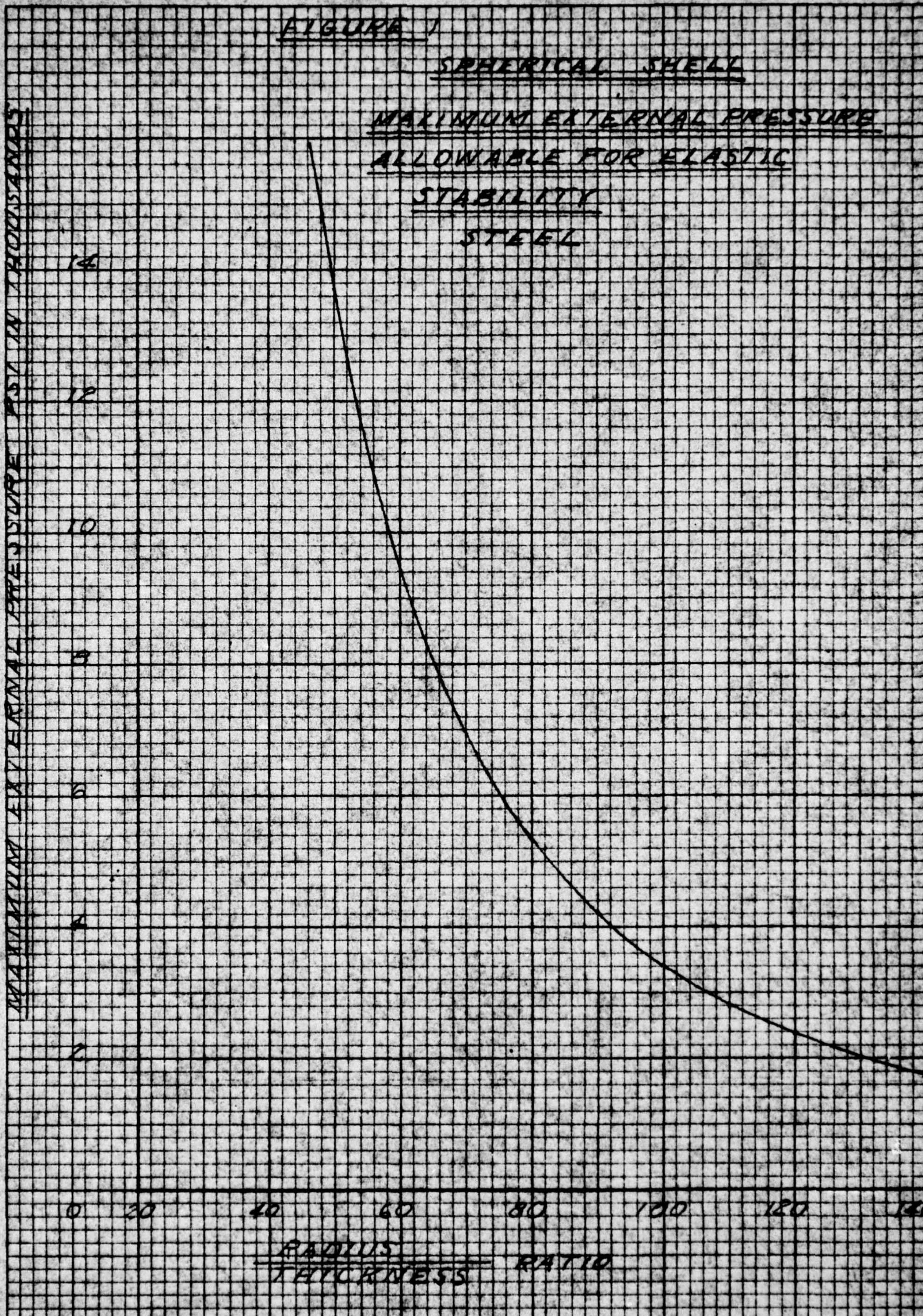


FIGURE 1
SPHERICAL SHELL
MAXIMUM EXTERNAL PRESSURE
ALLOWABLE FOR ELASTIC
STABILITY
STEEL
MAXIMUM EXTERNAL PRESSURE PSI IN THOUSANDS
14
12
10
8
6
4
2
0
20
40
60
80
100
120
140
RADIUS / THICKNESS RATIO

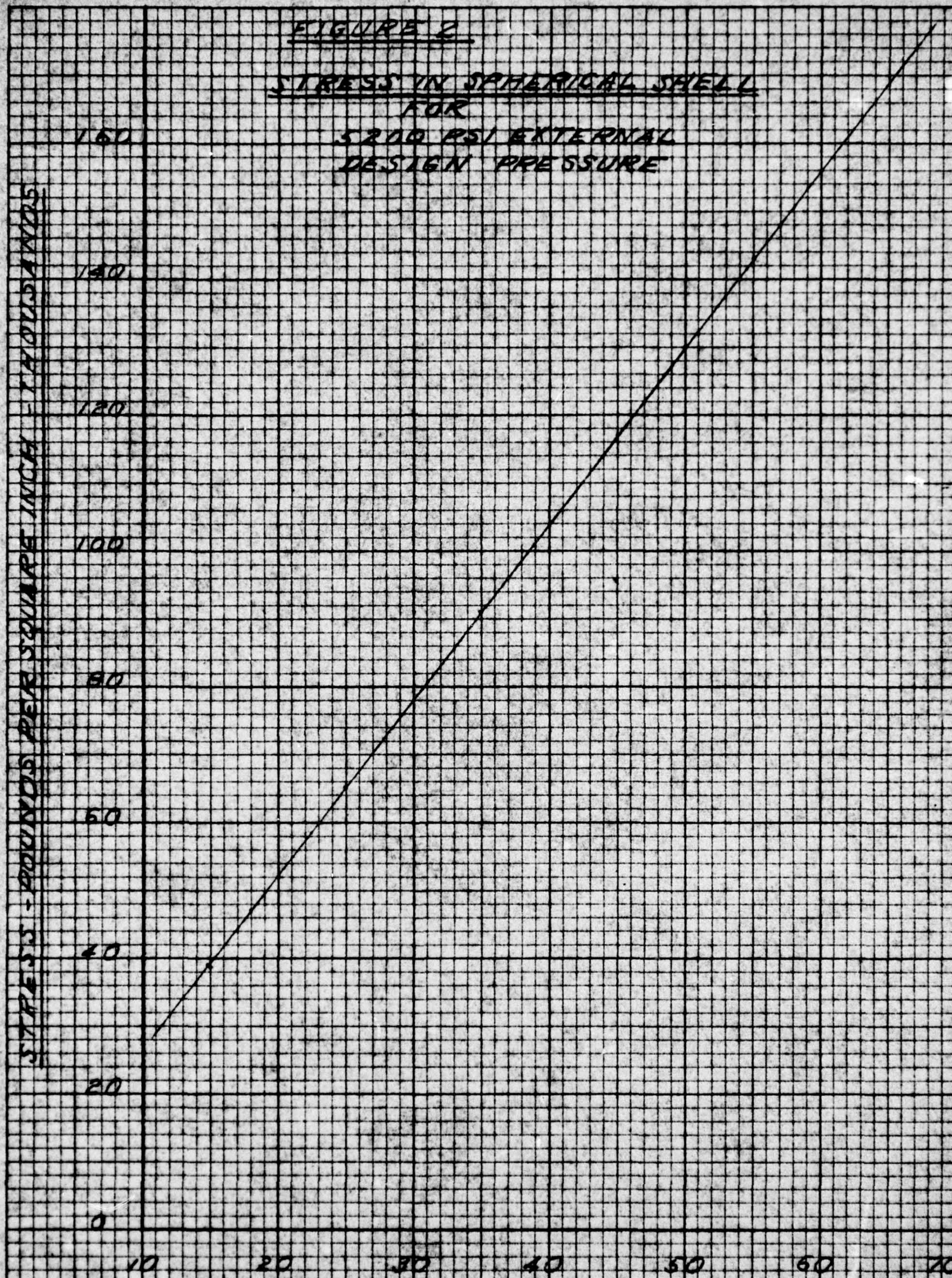


FIGURE 2
STRESS IN SPHERICAL SHELL
FOR
5200 PSI EXTERNAL
DESIGN PRESSURE
STRESS - POUNDS PER SQUARE INCH - THOUSANDS
0
20
40
60
80
100
120
140
160
10
20
30
40
50
60
70
RADIUS
SHELL THICKNESS
NO. 340R-10 DIETZGEN GRAPH PAPER
10 X 10 PER INCH
EUGENE DIETZGEN CO.
MADE IN U.S.A.

FIGURE 3

COMPRESSION

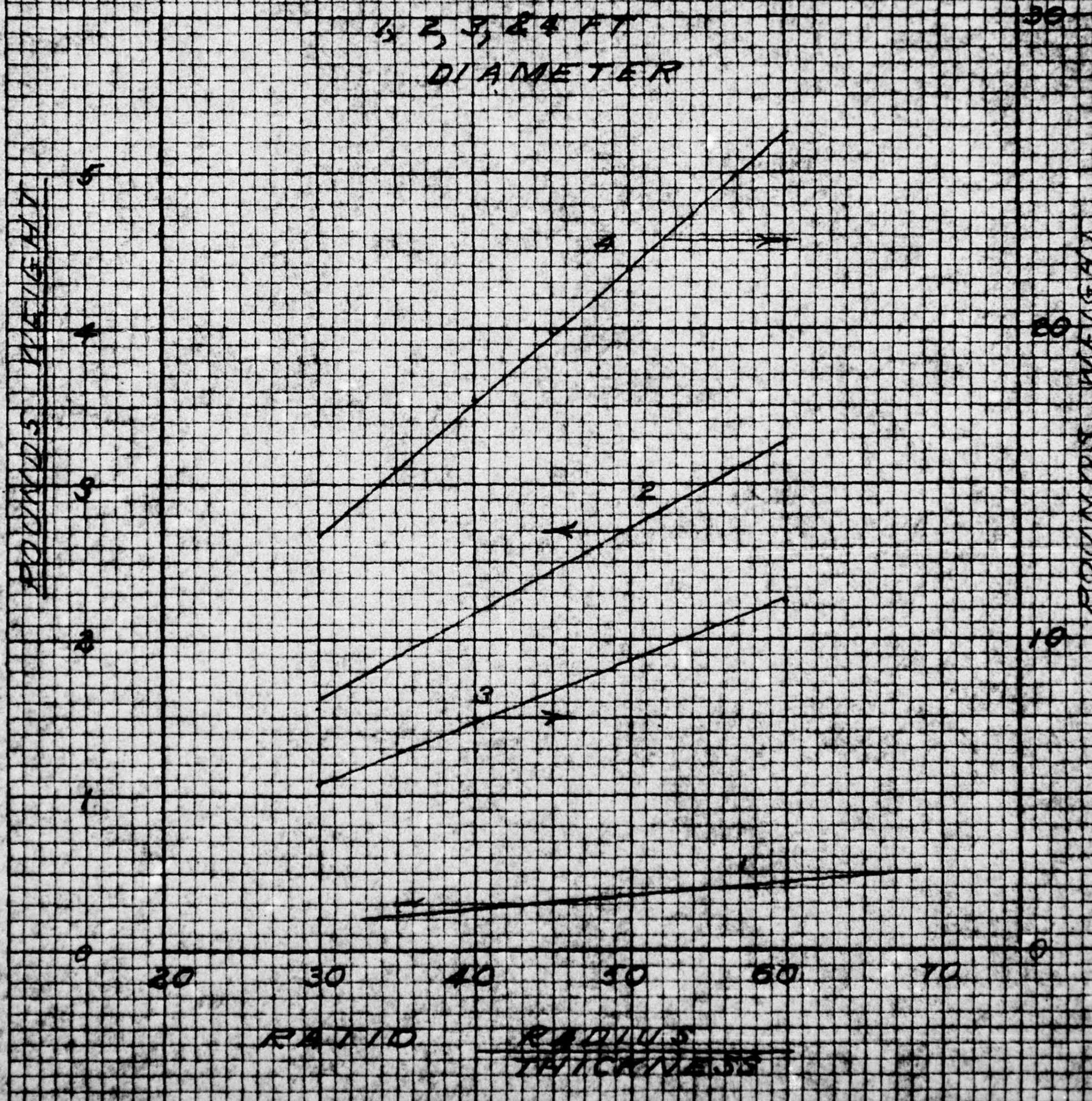
BOUYANCY WEIGHT CHANGE DUE TO HYDROSTATIC PRESSURE

AT 12,000 FT ρ=1.04

WEIGHT CHANGE PLOTTED AGAINST $\frac{\text{RADIUS}}{\text{THICKNESS}}$ RATIO OF SHELL

SPHERES

1, 2, 3, & 4 FT DIAMETER



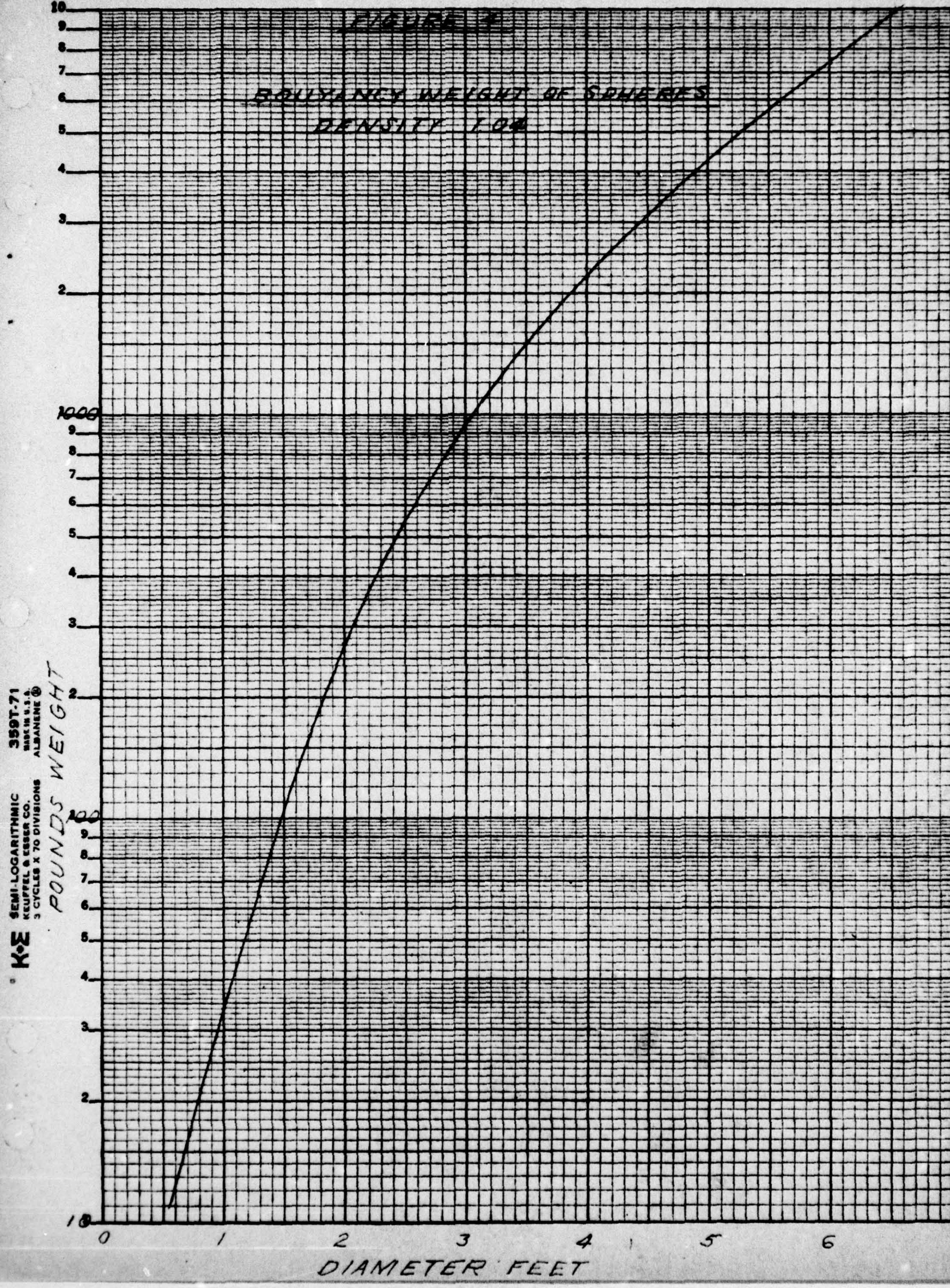
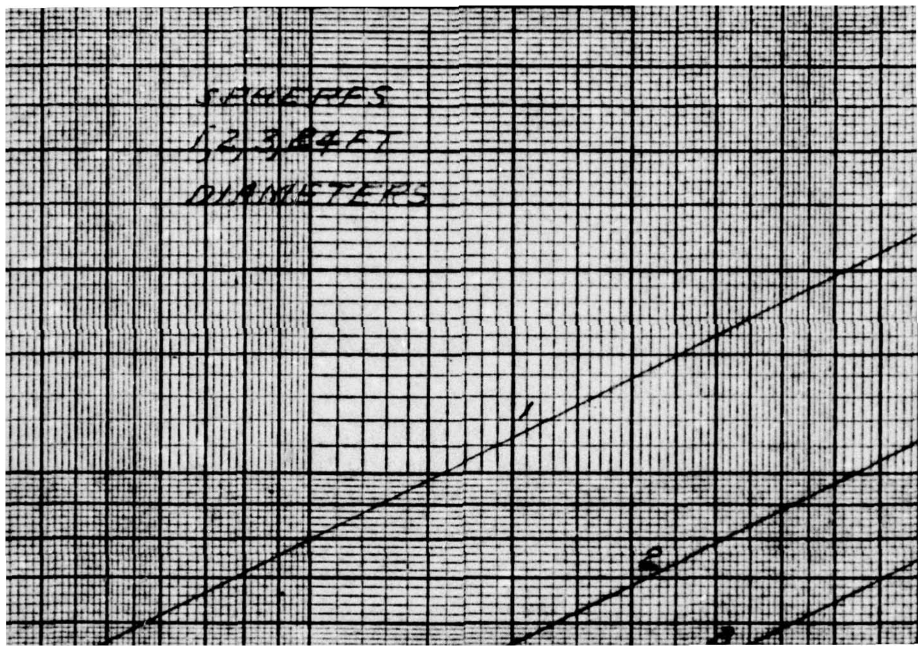


FIGURE 3
BOUYANCY WEIGHT OF SPHERES
DENSITY 1.04
POUNDS WEIGHT
DIAMETER FEET
10
1000
100
0
1
2
3
4
5
6
SEMI-LOGARITHMIC
KEUFFEL & ESSER CO.
3 CYCLES X 70 DIVISIONS
359T-71
ALBANENE


SPHERES
1,2,3,&4 FT
DIAMETERS
1
2
3

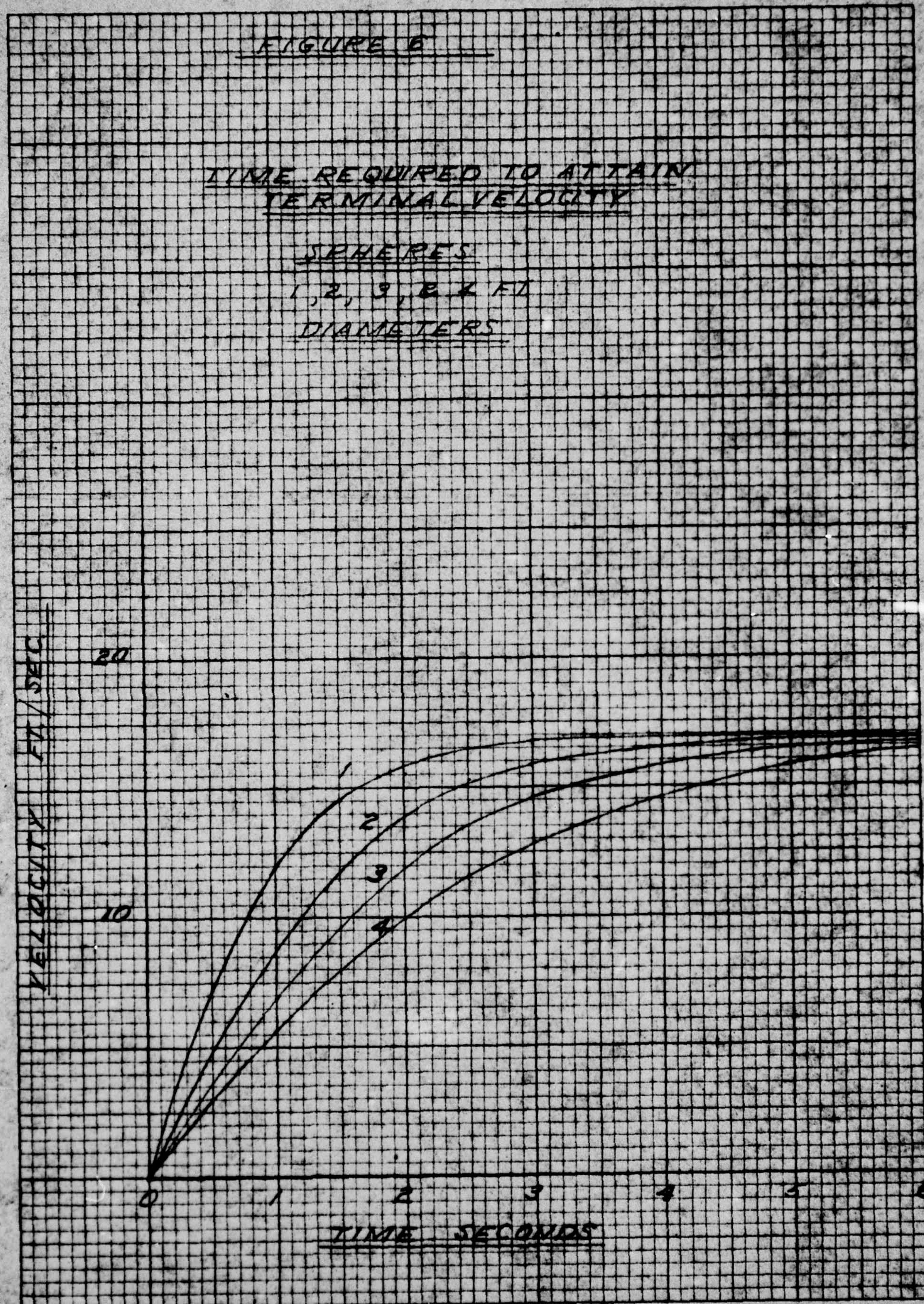


FIGURE 6
TIME REQUIRED TO ATTAIN TERMINAL VELOCITY
SPHERES
1, 2, 3, & 4 FT
DIAMETERS
VELOCITY FT/SEC
20
10
1
2
3
4
0
1
2
3
4
5
6
TIME SECONDS

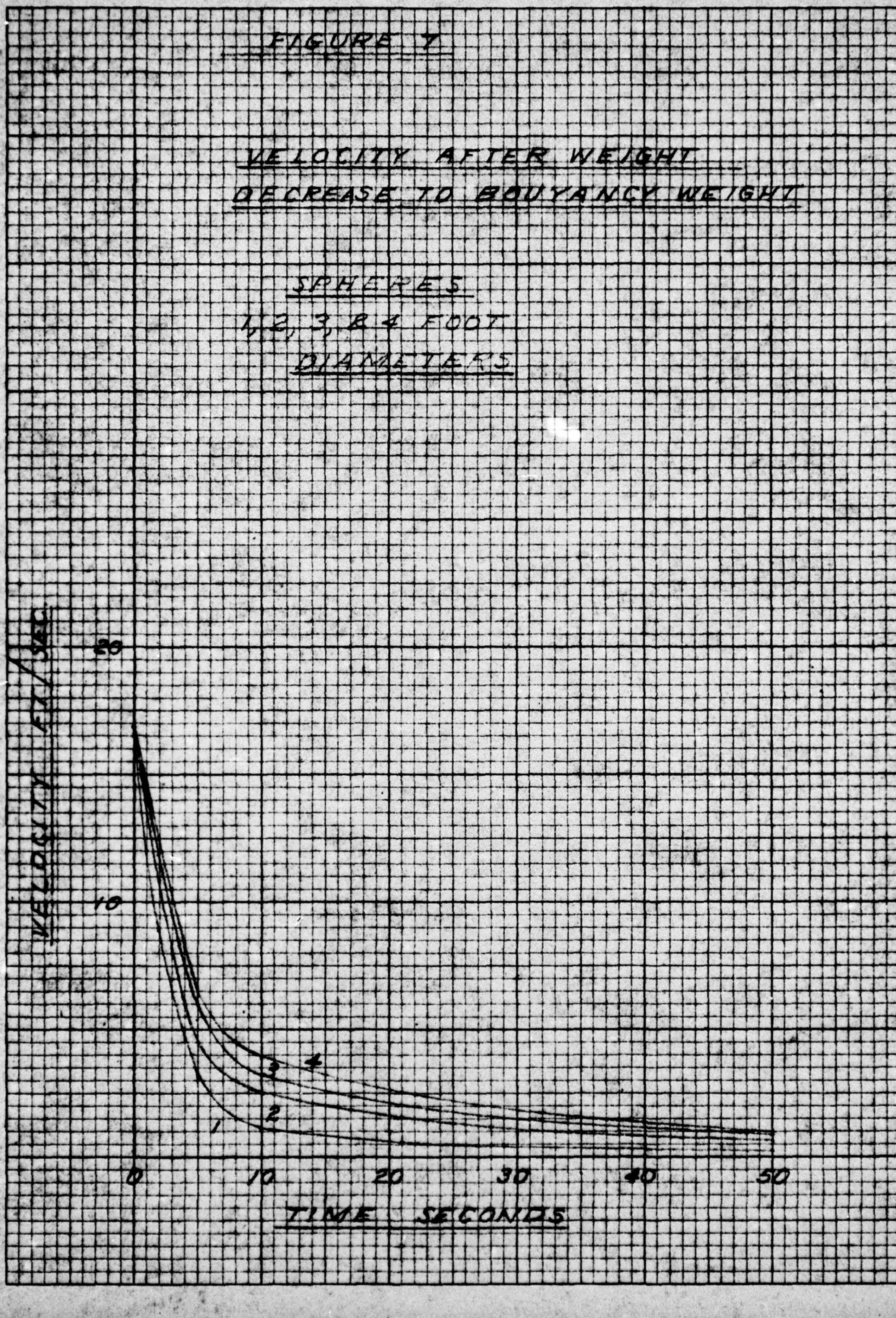


FIGURE 7
VELOCITY AFTER WEIGHT
DECREASE TO BOUYANCY WEIGHT
SPHERES
1, 2, 3, & 4 FOOT
DIAMETERS
VELOCITY FT/SEC
20
10
0
10
20
30
40
50
TIME SECONDS
1
2
3
4

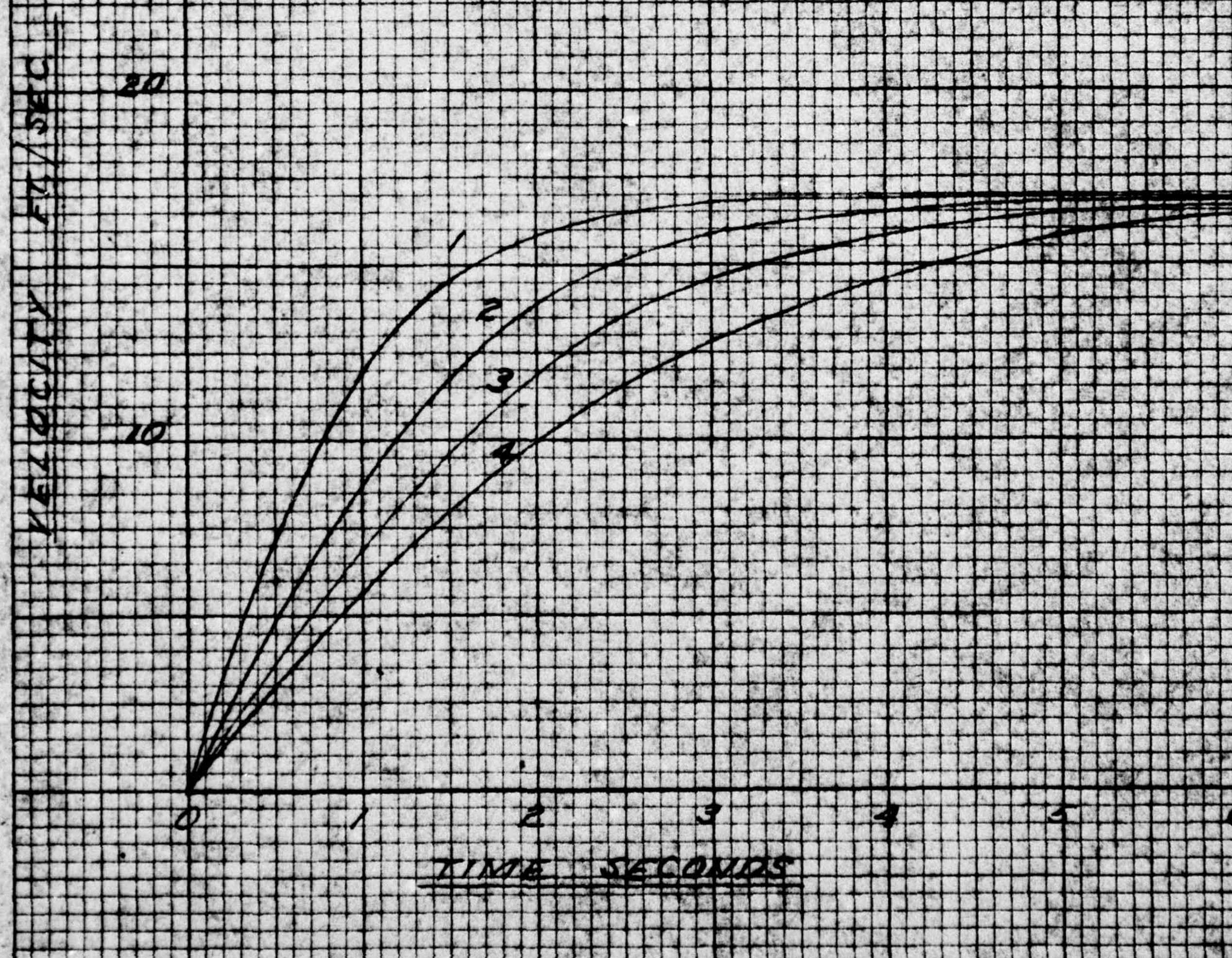
FIGURE 6

TIME REQUIRED TO ATTAIN TERMINAL VELOCITY

SPHERES

1, 2, 3, & 4 FT

DIAMETERS



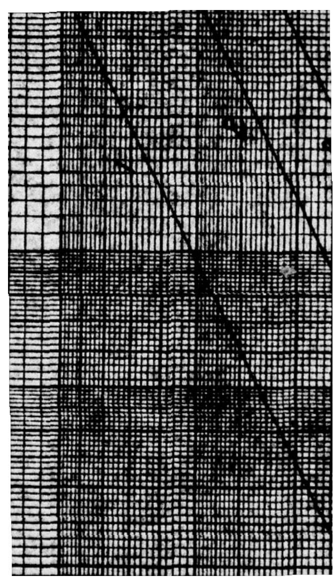


FIGURE 10

PERCENTAGE OF WEIGHT UNBALANCE FROM BOUYANCY PRODUCING DRIFT VELOCITIES FOR SPHERICAL SHELLS

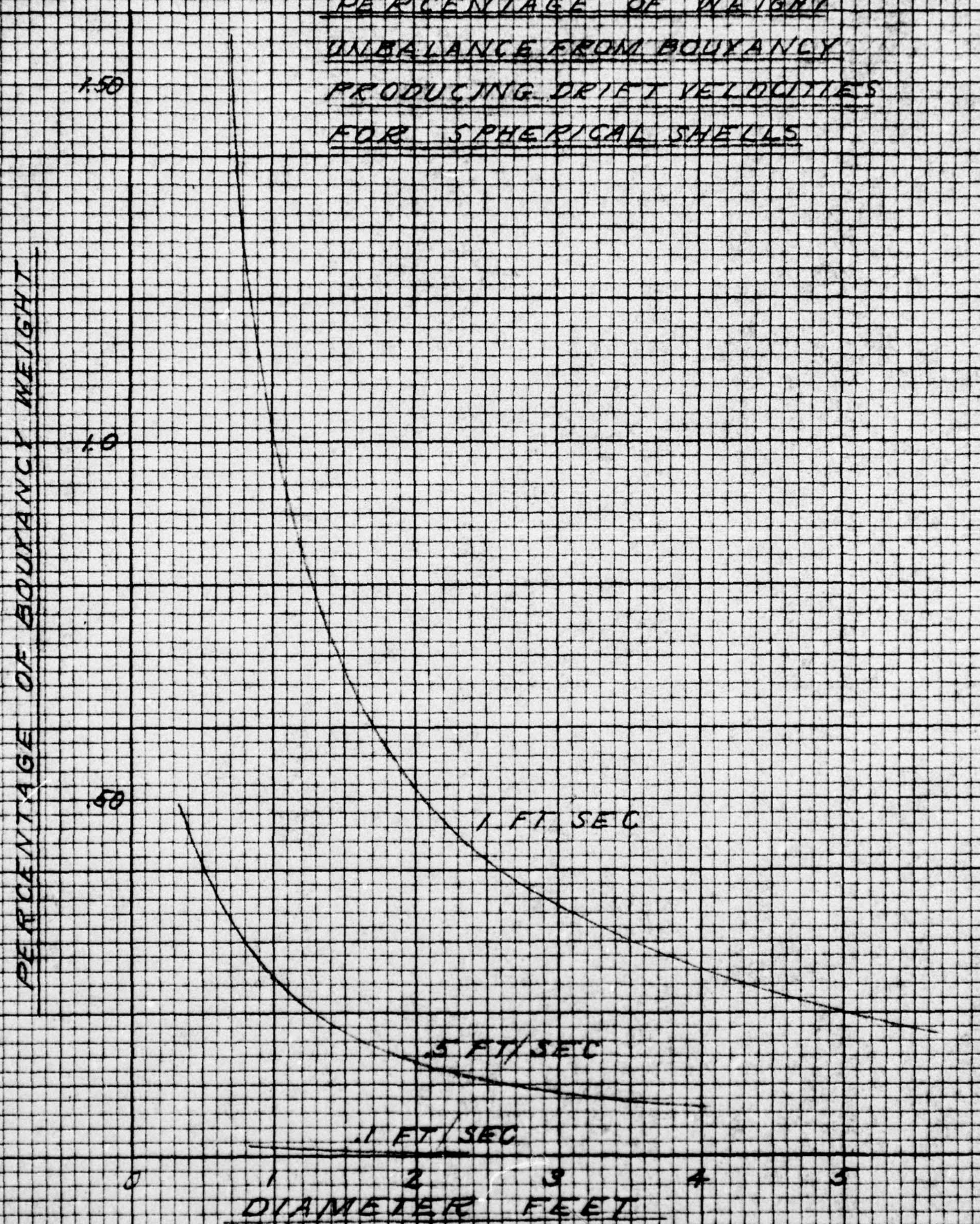


FIGURE 11.

DRIFT VELOCITIES PRODUCED BY WEIGHT UNBALANCE OF 100 FEET FROM POSITION OF NEUTRAL BOUYANCY.

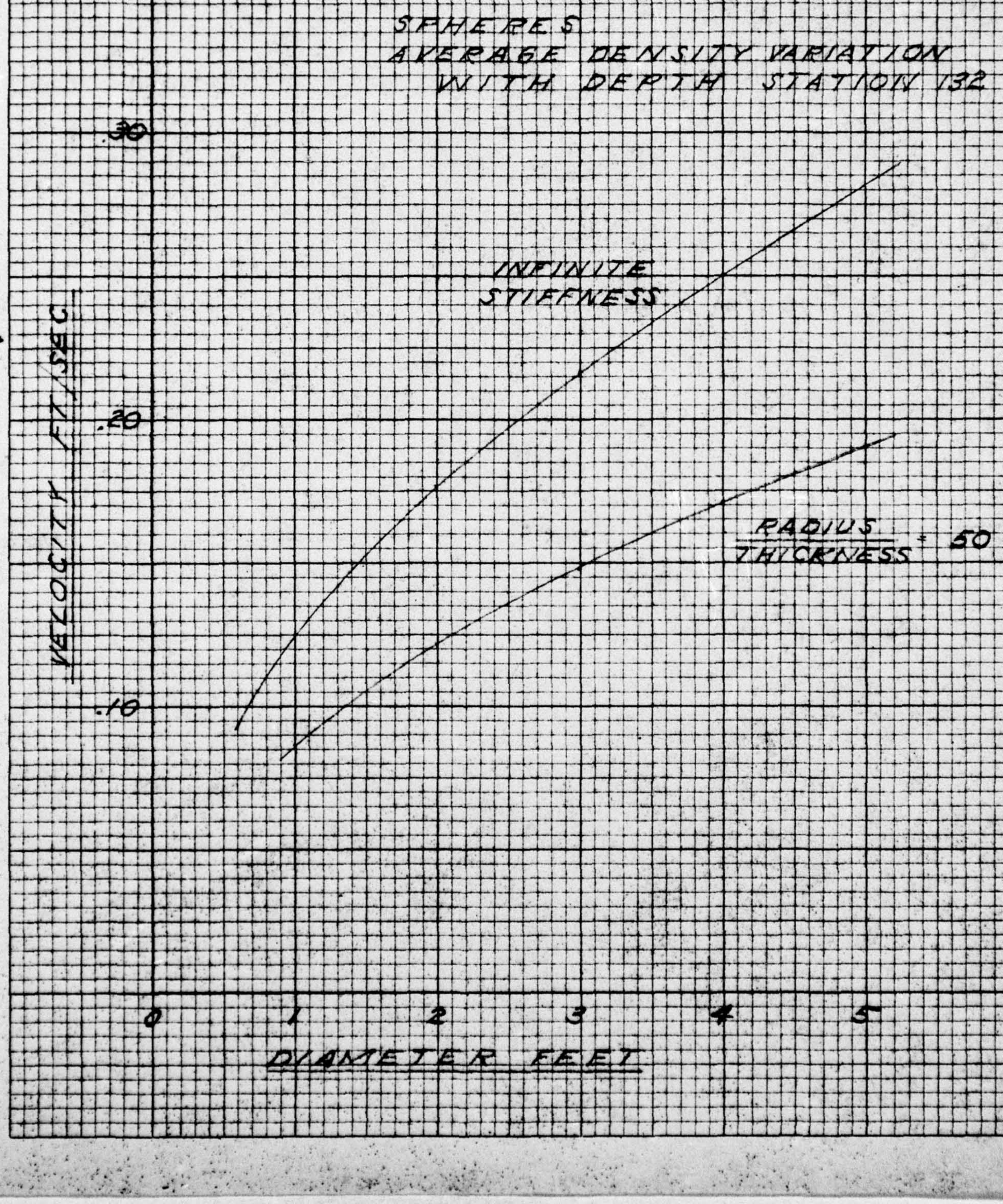
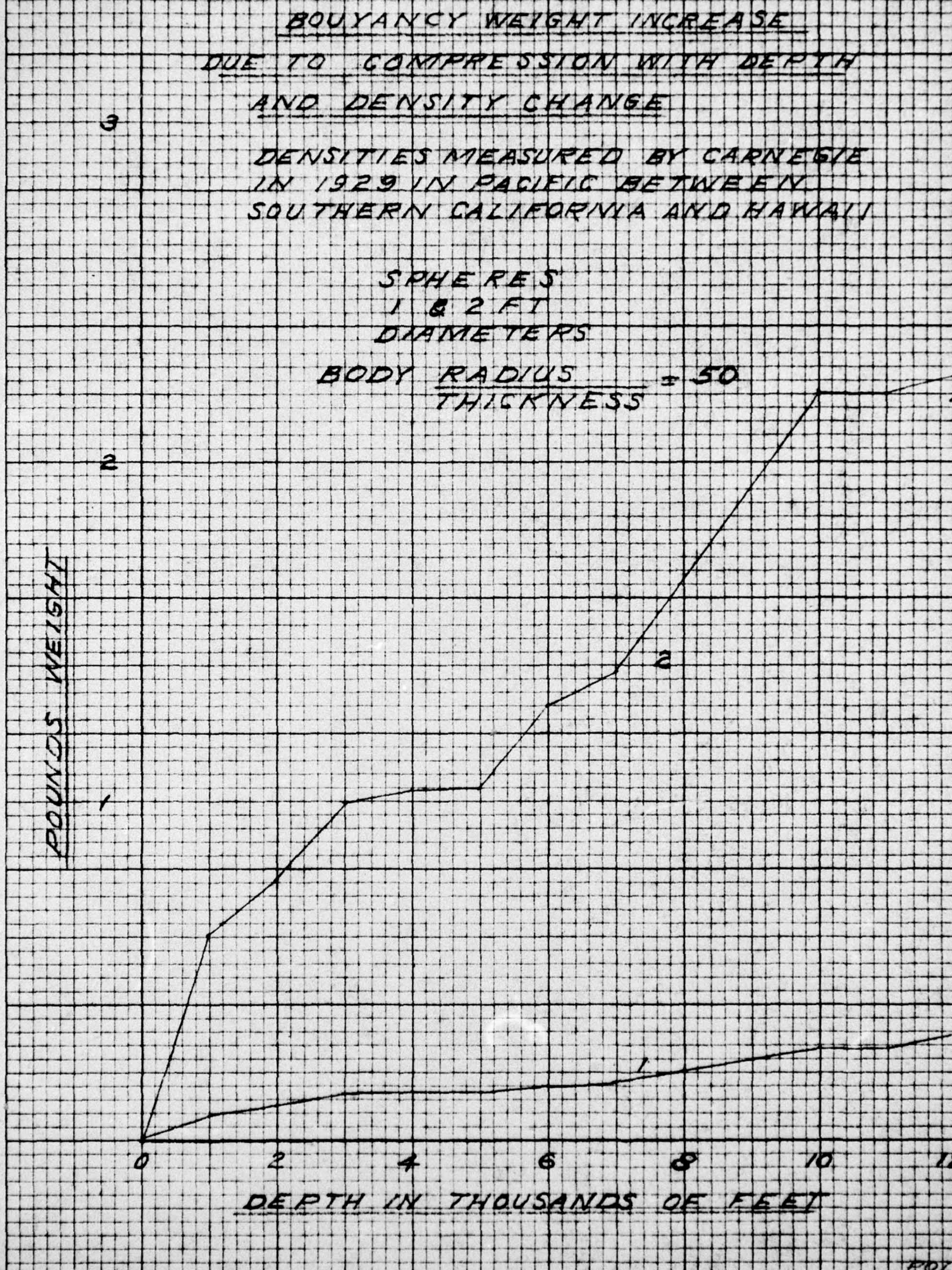


FIGURE 12


BOUYANCY WEIGHT INCREASE
DUE TO COMPRESSION WITH DEPTH
AND DENSITY CHANGE
DENSITIES MEASURED BY CARNEGIE
IN 1929 IN PACIFIC BETWEEN
SOUTHERN CALIFORNIA AND HAWAII
SPHERES
1 & 2 FT
DIAMETERS
BODY RADIUS / THICKNESS = 50
POUNDS WEIGHT
3
2
1
2
1
0
2
4
6
8
10
12
DEPTH IN THOUSANDS OF FEET
ROZ

## FIGURE 13

### BOUYANCY WEIGHT INCREASE DUE TO COMPRESSION AND DENSITY CHANGE WITH DEPTH

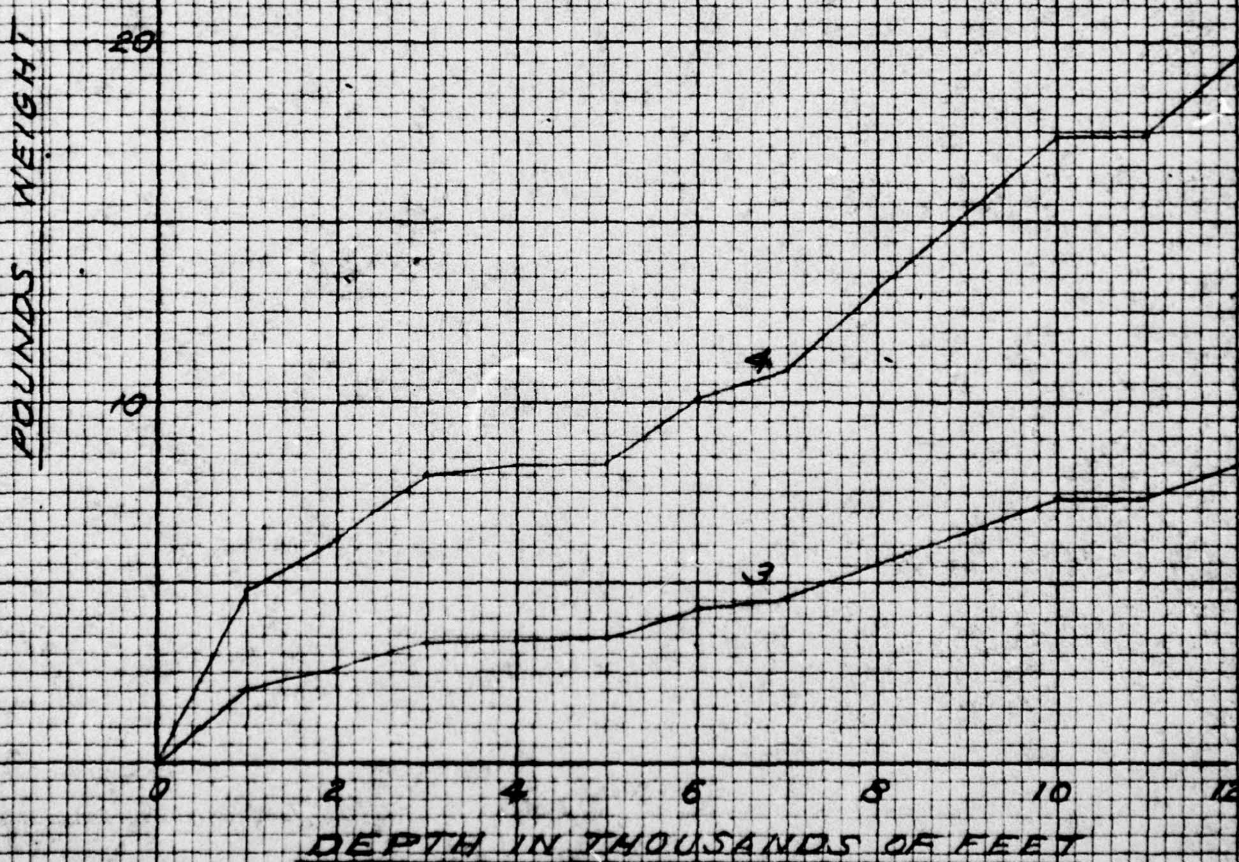
DENSITIES MEASURED BY CARNEGIE IN 1929 IN PACIFIC BETWEEN SOUTHERN CALIFORNIA AND HAWAII

SPHERES

3 & 4 FT

DIAMETERS

BODY $\frac{\text{RADIUS}}{\text{THICKNESS}} = 50$



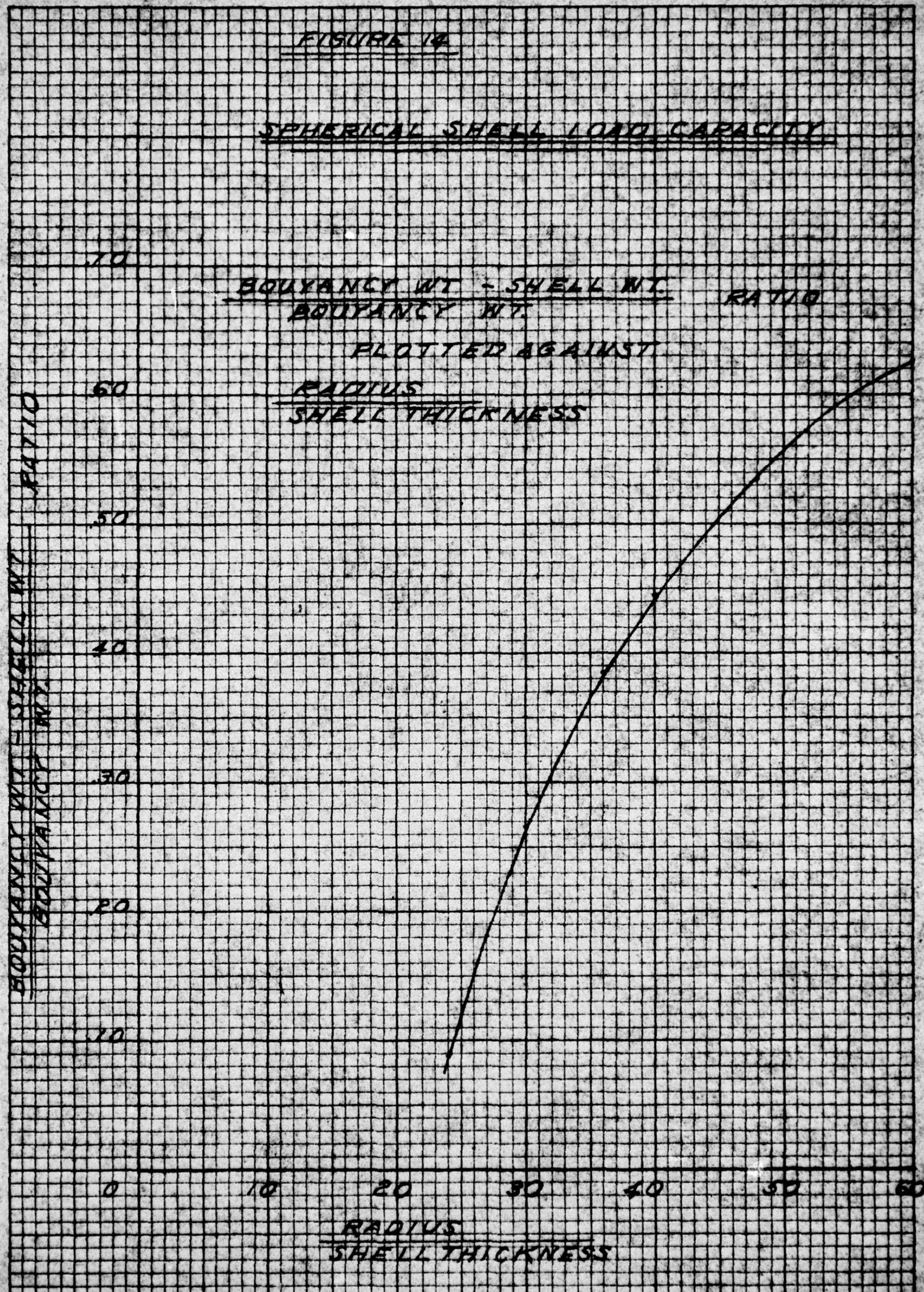



FIGURE 14

SPHERICAL SHELL LOAD CAPACITY

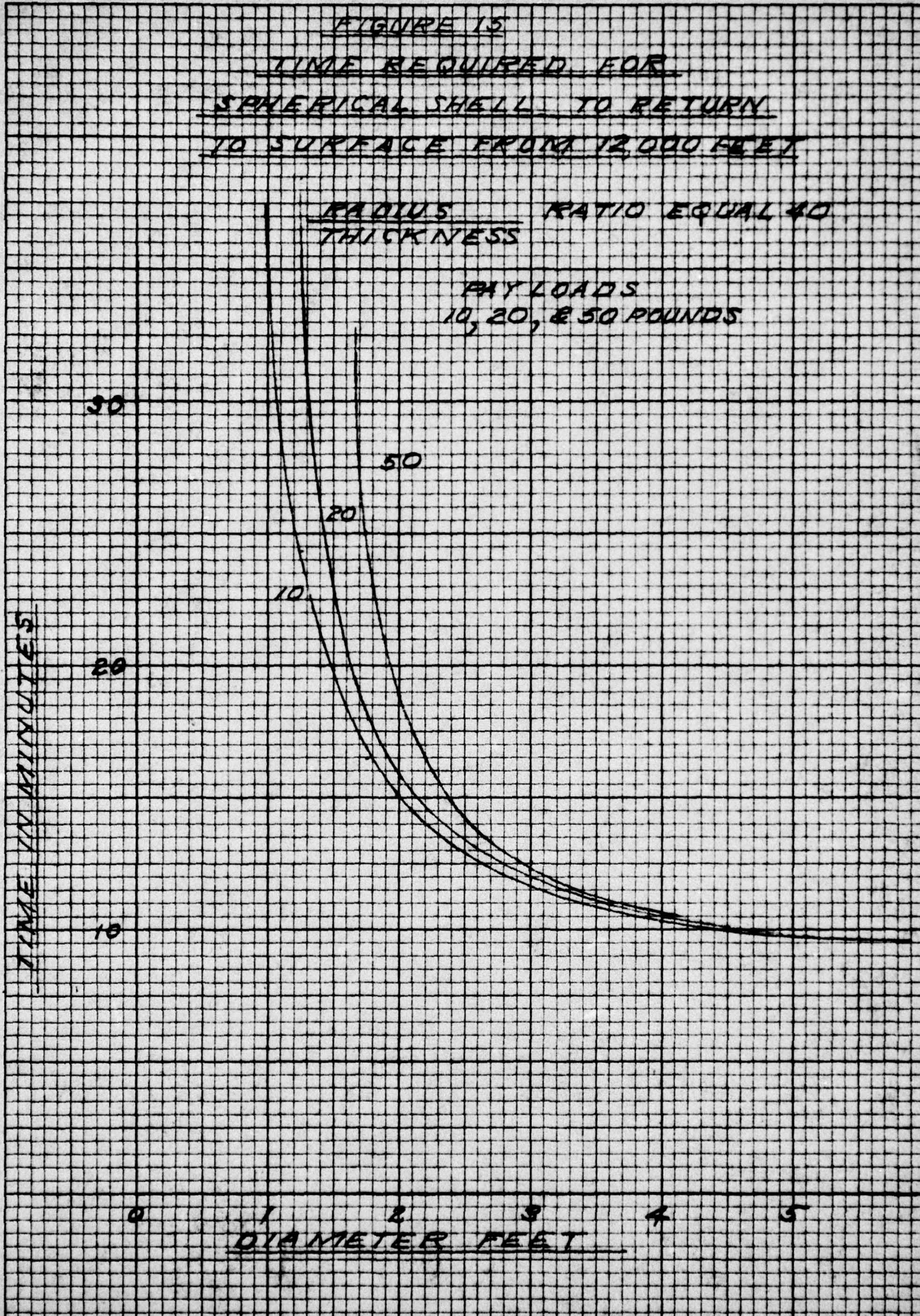



FIGURE 15
TIME REQUIRED FOR SPHERICAL SHELL TO RETURN TO SURFACE FROM 12,000 FEET